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Comparison of Outputs for Variable Combinations Used in Cluster Analysis on Polarimetric Imagery

by Melinda Petre

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14. ABSTRACT
Polarimetric imaging provides potential for highlighting man-made objects amongst complex natural backgrounds because man-made objects emit radiation with a higher degree of polarization than natural environments. More specifically, two techniques, Cluster Analysis (CA) and Principle Component Analysis (PCA) can be combined to process Stoke's imagery by distinguishing between pixels, and producing groups of pixels with similar characteristics. In this study, an algorithm which performs PCA and CA on three to five of the Stoke's imagery at a time was run on the same image subsection for all sixteen possible combinations in order to observe the differences between the combinations. After the data was compiled, the most basic cluster image and corresponding data was compared across all combinations. It was found that the majority of the groups had significantly different mean values at the 95% confidence level, and of this majority, most remained significant at the 99.9% confidence level. In addition, 14/16 of the data sets had a significant proportion of pixels in the smaller cluster group at the 95% confidence level, with 7/14 remaining significant at the 99.9% confidence level.

15. SUBJECT TERMS
Polarimetric, IR imagery, principle component analysis, cluster analysis

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1. Introduction/Background

Stokes imagery forms a basis consisting of $\{S_0, S_1, S_2, S_3\}$, where $S_1^2 + S_2^2 + S_3^2 \leq S_0^2$. ARL's specially calibrated FLIR camera captures the whole basis of data. From this basis, we specifically look at the linear polarimetric subset $\{S_0, S_1, S_2\}$, where S_0 is the incidence radiance and S_1 and S_2 specify the state of polarization. Stokes images can be used to calculate a variety of other metrics. However, this study only uses DOLP (degree of linear polarization) $\frac{\sqrt{S_1^2 + S_2^2}}{S_0}$ and ORT (orientation angle) $\frac{S_1}{S_2}$ (*1*).

Cluster Analysis groups pixels that have similar values together where similarity is measured using a distance metric. Since man-made objects emit radiation with a higher degree of polarization than complex natural backgrounds do, cluster analysis can help us separate these objects from their backgrounds. In particular, the cluster analysis highlights the regions which are more polarized and suppresses the less polarized regions (*2*). This will be useful for separating objects such as tanks, cars, trucks and buildings out of the brush. The cluster algorithm is hierarchical and agglomerative which means that every pixel in each image begins as an individual cluster and the two closest together fuse until the only remaining cluster contains all pixels (*2*). Likewise, distance is recalculated with every new member. Average linkage was used to create the clusters, defining distance between two clusters as the average between all members (*2*).

The goal of this study is to compare the results of cluster analysis when all sixteen possible combinations of input parameters are used in order to maximize the utility of the algorithm. The algorithm is outlined in ARL-TR-4216. All results were created using this algorithm run on images taken by BED. This paper introduces the methodology of the investigation and explores the statistical significance of the results in an effort to establish the differences amongst the variable combinations, with a hope of establishing an input preference.

2. Experiment/Calculations

The goal of this study is to compare the results of cluster analysis when all sixteen possible combinations of input parameters are used. To achieve this goal, multiple polarimetric images were explored in order to find a suitable subset for the investigation. The remainder of the study used only a single image. Once this image was selected, the algorithm was run over the subsection of this image containing the targets using all sixteen possible combinations of input

parameters: DolpOrtS0, DolpOrtS1, DolpOrtS2, DolpS0S1, DolpS0S2, DolpS1S2, OrtS0S1, OrtS0S2, OrtS1S2, S0S1S2, DolpOrtS0S1, DolpOrtS0S2, DolpOrtS1S2, DolpS0S1S2, OrtS0S1S2 and DolpOrtS0S1S2. The output from the algorithm included cluster images that diagrammed the group location for each pixel during all iterations, as well as the number of pixels in each group and the mean values for each of these groups and their standard deviations. From these outputs, specific values were gathered and compiled onto an Excel™ chart for further evaluation. For this study, the final iterations containing only two cluster groups were considered, where the two groups implied the target and background..

First, the mean values for the groups were statistically analyzed to see if the two groups were significantly different from each other. This comparison was completed using a simple hypothesis test for the difference of two means. The null hypothesis, $\mathrm{H}_0 : \mu_1 - \mu_2 = 0$ and the alternative hypothesis, $\mathrm{H}_\mathrm{A} : \mu_1 - \mu_2 \neq 0$ were evaluated. μ_1 and μ_2 represent the means of the two groups. Thus, the null hypothesis states that there is no significant difference between the means, whereas the alternative hypothesis implies that there is a significant difference between the means. This hypothesis was tested at both $\alpha = .05$ and $\alpha = .001$ significance levels. $\alpha = .05$ tells us that 95% of the time we can be sure that the results of the test are accurate, but $\alpha = .001$ represents an even stronger statement, stating that 99.9% of the time the results of the test are accurate. Once the significance levels were chosen, the $t_{critical}$ values were calculated, where n_1 is the number of pixels in the large group and n_2 the number of pixels in the small group:

$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n_1 + n_2 - 2\right) = t\left(.025, n_1 + n_2 - 2\right)$ for $\alpha = .05$ and

$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n_1 + n_2 - 2\right) = t\left(.0005, n_1 + n_2 - 2\right)$ for $\alpha = .001$ and recorded from the t-distribution table. Next, the t_{sample} values were calculated: $t_{\text{sample}} = \frac{(\bar{x}_1 - \bar{x}_2) - \mathrm{H}_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$. Thus, we can compare the values for $t_{critical}$ and t_{sample}. When $t_{\text{sample}} \geq t_{\text{critical}}$, the null hypothesis is rejected, implying that there is a significant difference between the means of the two groups. However, if $t_{\text{sample}} < t_{\text{critical}}$, the null hypothesis is accepted and there is no significant difference between the means of the two groups.

More specifically, here is an example of the hypothesis test using Dolp values from the DolpOrtS0 combination. From the data, $\bar{x}_1 = 0.095673$, the mean of the first group, and $\bar{x}_2 = 0.081788$, the mean of the second group. $n_1 = 943$, the size of the first group, $n_2 = 18$, the size of the second group, $\sigma_1 = 0.002203$, standard deviation of the first group, and $\sigma_2 = 0.013361$, standard deviation of the second group. The hypothesis test for $\alpha = .05$ progresses as follows:

$$\mathrm{H}_0 : \mu_1 - \mu_2 = 0$$

$$\mathrm{H}_\mathrm{A} : \mu_1 - \mu_2 \neq 0$$

$$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n_1 + n_2 - 2\right) = t\left(.025, 959\right) = 1.96$$

$$t_{\text{sample}} = \frac{\left(\bar{x}_1 - \bar{x}_2\right) - \mathrm{H}_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} = \frac{\left(0.095673 - 0.081788\right) - 0}{\sqrt{\frac{0.002203^2}{943} + \frac{0.013361^2}{18}}} = 4.407$$

This gives a t_{critical} of 1.96 and a t_{sample} of 4.407. Since $4.407 > 1.96$, $t_{\text{sample}} > t_{\text{critical}}$ and the null hypothesis is rejected. Thus, at the 95% confidence level, the means of the two groups are significantly different. However, since this analysis has a 5% error, the 99.9% confidence level using $\alpha = .001$ is also evaluated as follows:

$$\mathrm{H}_0 : \mu_1 - \mu_2 = 0$$

$$\mathrm{H}_\mathrm{A} : \mu_1 - \mu_2 \neq 0$$

$$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n_1 + n_2 - 2\right) t\left(.0005, 959\right) = 3.291$$

$$t_{\text{sample}} = \frac{\left(\overline{X}_1 - \overline{X}_2\right) - \mathrm{H}_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} = \frac{\left(0.095673 - 0.081788\right) - 0}{\sqrt{\frac{0.002203^2}{943} + \frac{0.013361^2}{18}}} = 4.407$$

This gives a t_{sample} of 4.407 and a t_{critical} of 3.291, where $4.407 > 3.291$ and thus $t_{\text{sample}} > t_{\text{critical}}$, so the null hypothesis is rejected, and there is a significant difference in the means at the 99.9% confidence level.

In addition to comparing the means of the two groups, the proportion of pixels in the smaller group was compared to zero in order to see if this proportion was significantly different from zero. A hypothesis test for significance was used for this as well, using the proportion calculated $\Pi = \frac{\#PixelsSmallGroup}{\#PixelsTotal}$. The hypothesis tested follows $\mathrm{H}_0 : \Pi = 0$ or $\mathrm{H}_\mathrm{A} : \Pi \neq 0$. The null hypothesis questions whether Π is the same as zero, or, as the alternative hypothesis states, Π is significantly different from zero. Once again, this was tested at both the 95% and 99.9% confidence levels, using $\alpha = .05$ and $\alpha = .001$. The critical value is calculated as such: $t_{\text{critical}} = t\left(\frac{\alpha}{2}, n-1\right) = t\left(.025, n-1\right)$ for $\alpha = .05$ and $t_{\text{critical}} = t\left(\frac{\alpha}{2}, n-1\right) = t\left(.0005, n-1\right)$ for

$\alpha = .001$, and the t-sample is calculated: $t_{\text{sample}} = \dfrac{(\hat{\mathrm{P}}) - \mathrm{H}_0}{\sqrt{\dfrac{\hat{\mathrm{P}}(1-\hat{\mathrm{P}})}{n}}}$. $\hat{\mathrm{P}}$ is the estimated proportion of pixels in the small group. If $t_{\text{sample}} \geq t_{\text{critical}}$ the null hypothesis is rejected, stating the proportion of pixels in the smaller group is significantly different from zero; however, if $t_{\text{sample}} < t_{\text{critical}}$, the alternative hypothesis is accepted and the proportion is significantly different from zero.

For an example from the analysis, consider $\hat{\mathrm{P}} = 0.018730489$, the estimated proportion of pixels in the small group from the DolpOrtS0 combination. The hypothesis test for $\alpha = .05$ follows:

$$\mathrm{H}_0 : \Pi = 0$$

$$\mathrm{H}_\mathrm{A} : \Pi \neq 0$$

$$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n-1\right) = t(.025, 960) = 1.96$$

$$t_{sample} = \frac{(\hat{\mathrm{P}}) - \mathrm{H}_0}{\sqrt{\dfrac{\hat{\mathrm{P}}(1-\hat{\mathrm{P}})}{n}}} = \frac{0.018730489 - 0}{\sqrt{\dfrac{0.018730489(1-0.018730489)}{960}}} = 4.283$$

This gives t_{critical} = 1.96 and t_{sample} = 4.283, and therefore $4.283 > 1.96$, and $t_{\text{sample}} > t_{\text{critical}}$ so the null hypothesis is rejected. Thus, at the 95% confidence level, the proportion of pixels in the small group for DolpOrtS0 is significantly different from zero. To strengthen this conclusion, look at the hypothesis test for $\alpha = .001$:

$$\mathrm{H}_0 : \Pi = 0$$

$$\mathrm{H}_\mathrm{A} : \Pi \neq 0$$

$$t_{\text{critical}} = t\left(\frac{\alpha}{2}, n-1\right) = t(.0005, 960) = 3.291$$

$$t_{\text{sample}} = \frac{(\hat{\mathrm{P}}) - \mathrm{H}_0}{\sqrt{\dfrac{\hat{\mathrm{P}}(1-\hat{\mathrm{P}})}{n}}} = \frac{0.018730489 - 0}{\sqrt{\dfrac{0.018730489(1-0.018730489)}{960}}} = 4.283$$

This gives t_{critical} = 3.291 and t_{sample} = 4.283, $4.283 > 3.291$ and $t_{\text{sample}} \geq t_{\text{critical}}$, thus, the null hypothesis is rejected and at the 99.9% confidence interval, the proportion remains significantly different from zero.

3. Results and Discussion

This investigation focuses on the outputs from the cluster algorithm analysis of one image subsection run with all possible variable input combinations. More specifically, the investigation uses the data from the two group clusters as outputted from the cluster algorithm, after it was run on the visible image subsection found in figure 1. As seen in this image, two large tanks reside in the center; one closer to the top and the other the bottom.

Figure 1. Visible image subsection.

The outputs from the algorithm included pictures showing which group the pixels ended up in based on the principle component analysis. Figure 2 shows the resulting groups from the image based on the DolpOrtS0 combination of variables. The red pixels represent the location of the object and the blue pixels show the background. Notice the main clump of red pixels lies in the center, approximately where the lower vehicle appears in figure 1. The algorithm determined at the two cluster level that the lower vehicle is more different from the background than the upper vehicle.

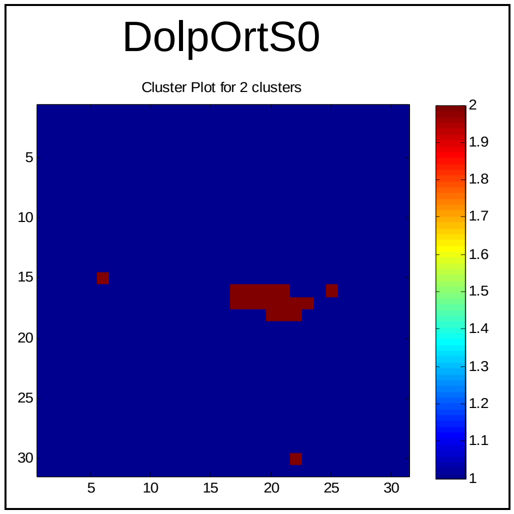

Figure 2. DolpOrtS0 cluster plot for two clusters.

Figure 3 shows the resulting two groups based on the DolpOrtS0S1S2 combination of variables. This image highlights a different area of the image than the previous image does, demonstrating the necessity of the investigation. While this report only shows a sample of the images, it is evident from the entire set that every combination of variables highlights a slightly different portion. Therefore, it becomes necessary to look at the different combinations prior to establishing a preference.

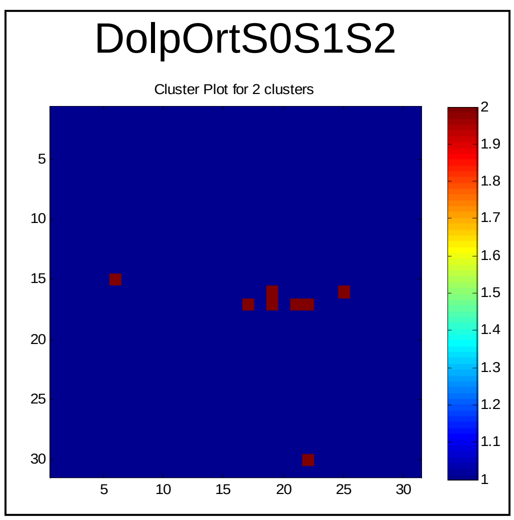

Figure 3. DolpOrtS0S1S2 cluster plot for two clusters.

The algorithm produced many outputs, ranging from images like those above, to statistics on the number of pixels, means and standard deviations of the clusters. From this data it is quite apparent that the different combinations place a different number of pixels in the smaller group. This number ranges from 2 to 51, with OrtS0S1 leading and DolpS1S2, DolpOrtS1S2, and

DolpS0S1S2 following furthest behind. The mean number of pixels in the small group was 14.7, the median 8, and the mode 2, 6, and 8. Figure 4 shows the distribution of pixels between groups 1 and 2 across all combinations of variables.

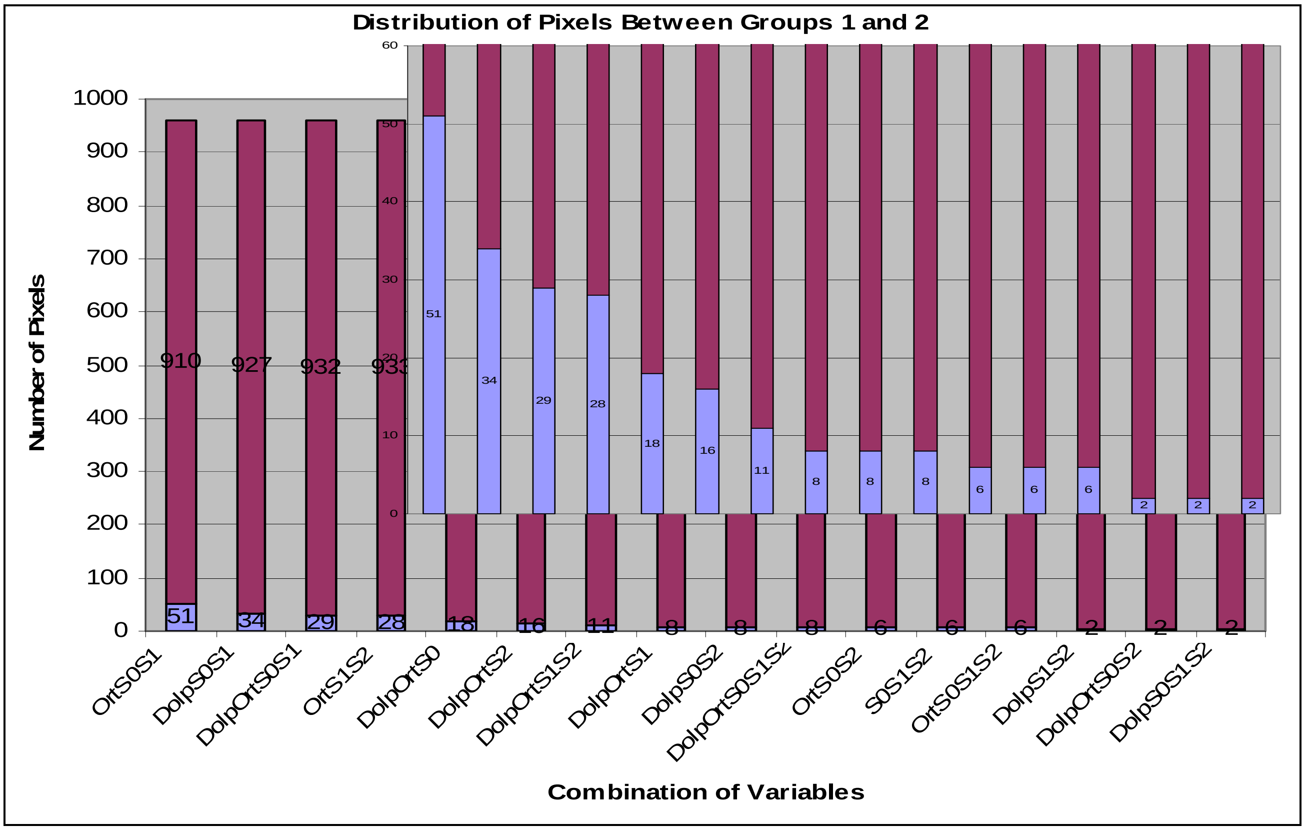

Figure 4. Distribution of pixels between groups 1 and 2.

The proportions of pixels in the small group were compared to zero, as explained in the previous section, to tell whether there were a significant number of pixels in the group. At the 95% confidence level, 14/16 proportions were significantly greater than zero. However, at the 99.9% confidence level, only 7/16 proportions remain significantly higher than zero. The more significantly different from zero the proportion is, the more likely that the analysis highlighted an object amongst the natural background. The following chart shows the specific results from the hypothesis testing. Listed next to the combination of variables are their relevant proportions, and either a yes or a no for the 95% confidence level and 99.9% confidence level, indicating as to whether the proportion is significant. The yellow highlighted “No” boxes indicate an insignificant proportion, and the white “Yes” boxes indicated a significant proportion.

Table 1. Results of the proportion hypothesis testing.

Combination	Proportion	95%	99.9%
DolpOrtS0	0.0187	Yes	Yes
DolpOrtS1	0.0083	Yes	No
DolpOrtS2	0.0166	Yes	Yes
DolpS0S1	0.0353	Yes	Yes
DolpS0S2	0.0083	Yes	No
DolpS1S2	0.0020	No	No
OrtS0S1	0.0530	Yes	Yes
OrtS0S2	0.0062	Yes	No
OrtS1S2	0.0291	Yes	Yes
S0S1S2	0.0062	Yes	No
DolpOrtS0S1	0.0301	Yes	Yes
DolpOrtS0S2	0.0020	No	No
DolpOrtS1S2	0.0114	Yes	Yes
DolpS0S1S2	0.0020	Yes	No
OrtS0S1S2	0.0062	Yes	No
DolpOrtS0S1S2	0.0083	Yes	No

This table displays the results from the proportion analysis. The first column, combination, refers to the combination of input values. The second column, proportion, gives the number of pixels in the small cluster over the number of pixels total. The third and fourth columns display the results of the hypothesis test for the 95% and 99.9% significance levels respectively.

The mean values of the two groups for each combination of variables were compared to see if there was a significant difference, as explained previously. As expected, it was found that the majority of the clusters had significantly different values for the mean of each group. Table 2 shows the specific results of the hypothesis testing. Listed next to each combination of variables are the three to five specific variables they are comprised of, and the results of the hypothesis test for a difference of mean values for each parameter at the 95% and 99.9% confidence levels. At the 95% confidence level, 9/55 means were insignificantly different and 21/55 of the mean values were insignificantly different at the 99.9% confidence level. The insignificant differences are marked with a yellow highlighted box and a “No”, and the significant differences are marked with a white “Yes” box.

Table 2. Results of the mean values of clusters comparison hypothesis testing.

Combination	Parameter	95%	99.9%
DolpOrtS0	Dolp	Yes	Yes
	Ort	Yes	Yes
	S0	Yes	Yes
DolpOrtS1	Dolp	No	No
	Ort	Yes	Yes
	S1	Yes	Yes
DolpOrtS2	Dolp	Yes	Yes
	Ort	Yes	Yes
	S2	Yes	Yes
DolpS0S1	Dolp	Yes	No
	S0	No	No
	S1	Yes	Yes
DolpS0S2	Dolp	Yes	Yes
	S0	Yes	No
	S2	Yes	Yes
DolpS1S2	Dolp	Yes	Yes
	S1	Yes	Yes
	S2	No	No
OrtS0S1	Ort	Yes	Yes
	S0	Yes	Yes
	S1	Yes	Yes
OrtS0S2	Ort	Yes	Yes
	S0	Yes	No
	S2	Yes	No
OrtS1S2	Ort	Yes	Yes
	S1	Yes	Yes
	S2	Yes	No
S0S1S2	S0	Yes	No
	S1	Yes	Yes
	S2	Yes	No
DolpOrtS0S1	Dolp	Yes	Yes
	Ort	Yes	Yes
	S0	No	No
	S1	Yes	Yes
DolpOrtS0S2	Dolp	Yes	Yes
	Ort	Yes	Yes
	S0	No	No
	S2	No	No
DolpOrtS1S2	Dolp	Yes	No
	Ort	Yes	Yes
	S1	Yes	Yes
	S2	Yes	Yes

Combination	Parameter	95%	99.9%
	S0	No	No
	S1	Yes	Yes
	S2	No	No
OrtS0S1S2	Ort	Yes	Yes
	S0	Yes	No
	S1	Yes	Yes
	S2	Yes	No
DolpOrtS0S1S2	Dolp	No	No
	Ort	Yes	Yes
	S0	Yes	No
	S1	Yes	Yes
	S2	Yes	No

This table summarizes the results from the hypothesis tests on whether or not there was a significant difference between the means of the two clusters. The first column, combination specifies the combination of input variables. The second column, variable, specifies the specific variable compared. Finally, the third and fourth columns display the results of the hypothesis test for the 95% and 99.9% significance levels respectively.

4. Summary and Conclusions

This investigation explored the output of a cluster analysis algorithm compared over all possible combinations of input parameters. Due to the difference in parameters, it was expected that the output would vary based on the combination. As seen in figure 3, the algorithm groups the pixels very differently across all combinations. In addition, it was expected that the differences in the means between the two groups would be significantly different because these groups were determined based on the individual pixels. It was found that the majority of the groups had significantly different mean values at the 95% confidence level, and of this majority, most remained significant at the 99.9% confidence level. Based on the variety of output as seen in figure 3, it was to be expected that some of the small groups would not contain a significant proportion of pixels compared to zero. It was found that 14/16 of the data sets had a significant proportion of pixels in the smaller, perceived object cluster group at the 95% confidence level, with 7/14 remaining significant at the 99.9% confidence level. The next step is to analyze even more specific statistics from these combinations and to repeat this analysis using more sample images with different backgrounds, targets, and weather conditions.

5. References

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2. Felton, M.; Gurton, K. P.; Ligon, D.; Raglin, A. *Discrimination of Objects Within Polarimetric Imagery Using Principal Component and Cluster Analysis*; ARL-TR-4216; U.S. Army Research Laboratory: Adelphi, MD, August 2007.

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